# Time-Resolved Ultraviolet Observations of the Globular Cluster X-ray Source in NGC 6624: The Shortest Known Period Binary System [1]

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## ABSTRACT

Using the Faint Object Spectrograph (FOS) aboard the *Hubble Space Telescope*, we have obtained the first time-resolved spectra of the King et al. ultraviolet-bright counterpart to the 11-minute binary X-ray source in the core of the globular cluster NGC 6624. This object cannot be readily observed in the visible, even from *HST*, due to a much brighter star superposed $< 0.1''$ distant. Our FOS data show a highly statistically significant UV flux modulation with a period of 11.46±0.04 min, very similar to the 685 s period of the known X-ray modulation, definitively confirming the association between the King et al. UV counterpart and the intense X-ray source. The UV amplitude is very large compared with the observed X-ray oscillations: X-ray variations are generally reported as 2–3% peak-to-peak, whereas our data show an amplitude of about 16% in the 126–251 nm range. A model for the system by Arons & King predicts periodic UV fluctuations in this shortest-known period binary system, due to the cyclically changing aspect of the X-ray heated face of the secondary star (perhaps a very low mass helium degenerate). However, prior to our observations, this predicted modulation has not been detected. Employing the Arons & King formalism, which invokes a number of different physical assumptions, we infer a system orbital inclination $35^\circ \lesssim i \lesssim 50^\circ$. Amongst the three best-studied UV/optical counterparts to the intense globular cluster X-ray sources, two are now thought to consist of exotic double-degenerate ultrashort period binary systems.

*Subject headings:* X-rays: stars — binaries: close — globular clusters: general

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## 1. Introduction

In some respects, the X-ray source X1820-30 in NGC 6624 is prototypical amongst the dozen highly luminous ($L_x \gtrsim 10^{36}$ erg s$^{-1}$) X-ray sources known in the Milky Way globular clusters. X1820-30 has been studied intensively in X-rays for several decades since its initial observation by *Uhuru* and SAS-3 (Giacconi et al. 1974; Jernigan & Clark 1979), was the first known X-ray burster (Grindlay et al. 1976), and shows quasi-periodic X-ray oscillations (Stella, White, & Priedhorsky 1987). On the other hand, X1820-30 is truly exceptional in at least one X-ray characteristic: it shows a low amplitude ($\sim 3\%$ peak-to-peak), but highly coherent, X-ray modulation with a period of 11 min (Stella, Priedhorsky, & White 1987; hereafter, SPW). The stability of this 11 min X-ray modulation is strongly indicative of an orbital period, and hence X1820-30 is thought to have the shortest known orbital period of *any* known binary system (SPW).

The compact accreting binary components in the intense globular cluster X-ray sources are generally thought to be neutron stars: this is suggested by the presence of X-ray bursts and by estimates of $\sim$1.5 $M_\odot$ for total system masses based on the typical displacement of the X-ray sources from the globular cluster cores (Grindlay et al. 1984). In the case of X1820-30 in NGC 6624, with its suspected 11 min orbital period, such a binary system must necessarily be tiny, with a binary separation of only a few tenths of $R_\odot$: separation $\sim 1.3 \times 10^{10}[M_{ns}(1+q)]$ cm, where $M_{ns}$ is the the neutron star mass in units of 1.4 $M_\odot$, and $q$ is the mass ratio (Arons and King 1993; hereafter, AK). Indeed the only mass-losing companion that will fit within such a tight binary system must be a degenerate dwarf (e.g., SPW; Verbunt 1987; AK) of very low mass: a plausible companion is a Roche-lobe filling helium degenerate (white) dwarf with mass $\sim$ 0.07 $M_\odot$ and radius $\sim 0.03 R_\odot$. In such a system, gravitational radiation alone can drive sufficient mass transfer to account for the high observed X-ray luminosity (SPW).

Although X-ray investigations alone have provided essential clues to the nature of the luminous globular cluster sources, even the initial identification (much less follow-up) of the optical/UV counterparts has proved frustratingly difficult for ground-based investigations due to the extreme crowding in most globular cluster cores. A notable exception is the optically bright counterpart AC 211 in M 15, whose high optical emissivity permitted early identification and study from the ground (Auriére, Le Fèvre, & Terzan 1984; Charles, Jones, & Naylor 1986). However, *Hubble Space Telescope* (*HST*) has markedly improved this situation in several globular clusters, and one of the notable early successes was the identification (using FOC images) of a highly ultraviolet object in the core of NGC 6624 as the likely counterpart to X1820-30 (King et al. 1993). A substantial majority of all the flux from the cluster at $\sim$1400 Å is attributable to just this one star. Groundbased study of this system is nearly infeasible, as the UV object lies only $0.08''$ from a presumably unrelated superposed star that is brighter than the King et al. counterpart in the optical.

AK provided a detailed model for the X1820-30 system. They invoke the previously suggested double-degenerate binary components, but their model also explains how the very intense emission

at X-ray and UV wavelengths are likely intimately related. They argue that a Rayleigh-Jeans tail of emission from the X-ray emitting region of the system would be grossly inadequate to directly explain the high observed UV flux; the UV emission must therefore arise from reprocessing of X-rays intercepted by the companion star and the accretion disk, with the bulk of the UV emission arising in reprocessing from the disk. Moreover, although the King et al. FOC data did not permit a sensitive search for UV variability, AK nonetheless further *predicted* that the UV flux should exhibit a modest (∼10%) modulation at the 11 min X-ray period, as the X-ray heated face (heated to T$\sim 10^5$K) of the low-mass degenerate companion is alternately visible to and hidden from the observer in its orbit about the neutron star.

Here, we report on our ultraviolet *HST* Faint Object Spectrograph (FOS) observations of the King et al. counterpart in NGC 6624. Although the time-averaged UV spectrum reveals no strong features, our FOS data are time-resolved and provide the first sensitive search for UV modulations at the 11 min X-ray period (see also Anderson et al. 1996). The *HST* observations are described and the time-averaged UV spectrum presented in §2. Our analysis of the FOS data for evidence of an 11 min UV modulation is described in §3. Some implications of our results are discussed in §4, especially with reference to the AK model.

## 2. *HST* Observations and the Time-Averaged UV Spectrum

On 1996 May 1 and 2 UT, we obtained low-resolution ultraviolet spectrophotometry from *HST* of the King et al. candidate. The data were taken with the G160L grating and FOS blue detector (broad 1150-2500 Å coverage, but low spectral resolution $\lambda/\Delta\lambda = 250$) with the $0.4''$ paired apertures. Eight-hundred separate FOS spectra were taken in "RAPID" mode, with a new spectrum taken every ∼15 s while the target was visible from *HST*; the data were collected during 21 distinct cycles of the 11 min X-ray period (and span 36 cycles). The FOS spectra have undergone the standard reductions performed on all such data processed through the STScI's pipeline reduction software.

The observed time-averaged UV spectrum is displayed in the upper panel of Fig. 1., and the lower panel shows the dereddened time-averaged spectrum assuming a reddening to the cluster of $E(B-V) = 0.25$ (Rich, Minniti, & Liebert 1993). The observed flux agrees reasonably well with the earlier FOC estimate by King et al. (1993): the value at 1400 Å is only about 35% lower in our FOS spectrum than that estimated by King et al. based on broadband FOC images (and of course the object may exhibit long-term variability in any case). The time-averaged observed spectrum is largely featureless at the low resolution and modest S/N of these FOS data, except for Ly$\alpha$ and the 2200 Å interstellar feature. (There could also be extremely weak NV $\lambda\lambda$ 1238, 1242 in emission, but our current data lack adequate S/N and resolution to confidently confirm or rule this out.) The Ly$\alpha$ emission is consistent with being largely geocoronal, as the total line strength is comparable to the geocoronal emission seen in the sky-aperture, but we cannot rule out some contribution from (or even net Ly$\alpha$ absorption toward) the binary system. The adopted

cluster reddening successfully removes the bulk of the prominent 2200 Å interstellar feature, and the dereddened FOS spectrum of Fig. 1 (lower panel) is fit well by a power-law $f_\lambda \propto \lambda^{-3.0}$. The latter is in good agreement with the slope of −3.2 estimated by King et al. (1993) from their comparison of dereddened optical and UV broadband FOC images.

## 3. Time-Resolved UV FOS Spectrophotometry

Information on UV spectral variability at a variety of timescales, and in a variety of different UV wavelength bandpasses, may be derivable from these FOS data. However, especially motivated by the AK model prediction, our initial focus is on the most straightforward (and potentially best S/N) search for broadband UV variability at the 11 min X-ray period. We do this broadband search merely by summing together the UV counts collected in 180 diodes of the FOS blue detector that sample the 1st-order G160L spectrum from 1265 Å to 2510 Å. This broadband UV count summation is done for each of the 800 individual “RAPID” readouts. Note that this wavelength bin purposefully starts conservatively longward of Ly$\alpha$, which is plausibly mainly of geocoronal origin. After correction for the detector noise background, we obtain in this way a simple measure of the broadband UV lightcurve of the system. The time resolution of these UV lightcurve data is ∼15 s, but the data are not uniformly sampled over the entire span of the *HST* observations due to earth occultations.

We use both Fourier power spectra (e.g., Roberts, Lehár, & Dreher 1987) and phase dispersion minimization (PDM) approaches (Stellingwerf 1978) to search for evidence of a broadband UV periodicity. For example, the upper panel of Fig. 2 shows a normalized Fourier power spectrum for the 1265-2510 Å broadband lightcurve data. For both Fourier and PDM approaches the strongest period detected is centered near 11.47 min. The UV broadband period is very similar to the known 685 s X-ray modulation (agreeing to within the expected Nyquist frequency resolution limitations for our observations, which span ≈400 min). It is clear that the statistical significance of our detection is very high indeed. The probability of an accidental peak due to random noise in a given bin of a Fourier power spectrum normalized to unity in the continuum is exponentially distributed, implying extremely small accidental occurrence probabilities (formally of order $e^{-39}$) in the case of our Fig. 2. Although this calculation cannot be taken literally, as the continuum normalization depends somewhat on the range of selected frequencies, our detection of the UV modulation is obviously firm. Hence, these FOS observations provide the first detection of an 11 min modulation from X1820-30 outside the X-ray regime.

Additionally, we have least-squares fitted a simple sinusoid to the 800 data points of our broadband UV lightcurve. This nonlinear least-squares approach yields the following best-fit parameter values and associated *formal* errors, once again reaffirming the high confidence of the detection of an 11 min modulation in these data: half-amplitude of 7.8±0.7%, period of 11.46±0.02 min, and epoch of maximum light at (heliocentric) $JD = 2450205.1926 \pm 0.0002$. The broadband UV lightcurve folded with these best-fit period/epoch values, and with lightcurve data-points

further binned in phase to reduce counting noise, is shown in the lower panel of Fig. 2. While the folded and phase-binned UV lightcurve appears reasonably fit by a sinusoid, a more complicated lightcurve is not ruled out (e.g., in fitting a sinusoid to the full unbinned lightcurve data, the reduced chi-square is $\approx 1.4$).

The strength with which the 11 min UV oscillation is detected across the broad 1265-2510 Å band suggests the feasibility of detecting a wavelength-dependence to the modulation. In various trials, we subdivided the FOS broad UV spectral coverage into finer wavelength bins, generated separate lightcurves for each bin, and reran the Fourier, PDM, and non-linear least squares analyses separately for each lightcurve. For example, in one particular trial we subdivided the FOS spectral coverage into 4 wavelength bins (each about 300 Å wide), yielding 4 distinct lightcurves derived from bins respectively centered near 1400 Å, 1700 Å, 2000 Å, and 2300 Å. In all trials, the lightcurve associated with each wavelength bin yielded a significant detection of the 11 min oscillation. But curiously, *within* each trial the values of the best-fit periods for two (or more) of the different-wavelength lightcurves were discrepant at the $\sim 2\sigma$ level from one another, taking the formal least-squares error bars at face value. This suggests that either the formal least-squares error bars on the period are artificially small, or that there is some real (but at best quite marginally detected) variation of the observed modulation period with wavelength. As the period and epoch in such a fit are strongly correlated, this might alternatively suggest a variation of the phase epoch with wavelength. Therefore, we hereafter conservatively adopt the typical *rms* deviations about the means seen in these various trials as more representative of the actual uncertainties for the period and epoch of the UV modulation: these deviations are $\pm 0.04$ min for the period and $\pm 0.8$ min ($\pm 0.0006$ days) for the phase epoch. From these same trials, we also find that our data are compatible with, but do *not* require, a small trend in UV oscillation amplitude with wavelength. For example, for the aforementioned trial subdividing into 4 wavelength bins (each $\sim$300 Å wide), the respective best-fit sinusoid half-amplitudes of the 4 lightcurves are 8.8±1.5%, 8.5±1.3%, 7.7±1.4%, and 6.9±1.0%.

## 4. Discussion and Conclusions

The time-averaged spectrum of Fig. 1 is clearly that of a highly ultraviolet object. This UV spectrum is consistent with an approximately power-law shape—nearly Rayleigh-Jeans in slope but somewhat more modest, as previously suggested by King et al. based on their broadband FOC images—after correction for plausible reddening to the cluster. As they discuss, such a broad spectral energy distribution is in approximate agreement with the predictions of the AK model in which the bulk of the UV (time-averaged) flux arises from reprocessing of X-radiation off the accretion disk. The consistency of the required reddening correction needed to remove the 2200 Å feature from our FOS spectrum clearly locates this UV object at a distance comparable to that of the globular cluster NGC 6624 (confirming at least that the UV-object cannot be markedly foreground).

At the most basic level our detection of the 11 min UV periodicity—a periodicity previously known only in X-rays—confirms unequivocally that the King et al. UV-bright object is most certainly the counterpart to the luminous X-ray source in NGC 6624. We hasten to point out that only the most cynical might have questioned this identification in any case, given the extraordinary ultraviolet time-averaged flux detected by King et al.

As noted in the introduction, the AK model for the X1820-30 system invokes but expands upon the previously suggested (e.g., SPW; Verbunt 1987) double-degenerate binary model (e.g., helium degenerate dwarf losing mass onto an accretion disk around a neutron star companion). Moreover, AK *predicted* that the UV flux should exhibit a ∼5–10% modulation at the 11 min X-ray period, as the X-ray heated face of the low-mass degenerate companion is alternately presented and hidden from the observer in its orbit about the neutron star. Our detection of an 11 min UV modulation with approximately the predicted amplitude must be viewed as strongly suggestive that at least some aspects of the AK double-degenerate model are correct.

If we adopt the formalism of the AK model, the observed amplitude of the UV modulation provides information on the binary orbital inclination angle $i$. The modulation relation derived by AK predicts a half-amplitude of $\epsilon_\nu \sin(i)/[\cos(i)+\epsilon_\nu \sin(i)]$, where $\epsilon_\nu$ is the ratio of the low-mass degenerate dwarf's X-ray reprocessing luminosity to the reprocessing luminosity of one face of the accretion disk. An approximate value of $\epsilon_\nu$ may be obtained from Fig. 2 of AK; we estimate $\epsilon_\nu \sim 0.09$ at 1980 Å, where the latter wavelength corresponds to the count-weighted mean wavelength of our 1st-order FOS spectrum. The UV oscillation amplitude measured from our data thus corresponds to $i \approx 43^\circ$ $(-9^\circ, +8^\circ)$ in the AK model, where the quoted uncertainty considers only the *formal* $3\sigma$ limits on the best-fit sinusoid amplitude. (These formal errors on the inclination, of course, do not account for systematic uncertainties associated with simplifying model assumptions, e.g., shadowing of the secondary by the disk is neglected).

The AK formalism also predicts an increasing oscillation amplitude toward shorter wavelengths, with $\epsilon_\nu$ and the oscillation amplitude $\sim 1.4\times$ larger at 1400 Å than at 2300 Å. Our data (see §3) yield a best-fit amplitude near 1400 Å which is $\approx 1.3 \pm 0.3$ times larger than that near 2300 Å, and thus are also consistent with this aspect of the AK model, but lack sufficient precision to provide a definitive test.

In closing, it is also of interest to note that based on WFPC2 photometric monitoring in the near-UV, Homer et al. (1996) have recently concluded that a second globular cluster X-ray source counterpart, "Star S" in NGC 6712 (Bailyn et al. 1991; Auriére & Koch-Miramond 1992; Anderson et al. 1993), is also a double-degenerate with an ultrashort 20.6 min binary orbital period. Moreover, the (albeit very low S/N) dereddened FOS ultraviolet spectrum of "Star S" in NGC 6712 displayed in Downes, Anderson, & Margon (1996) also rises steeply toward shorter wavelengths, and hence the "Star S" UV spectral energy distribution may at least resemble that of the King et al. counterpart in NGC 6224. At the very least it is a curious result—and perhaps a much more fundamental one—that among the 3 best-studied counterparts (AC 211 in M 15,

"Star S" in NGC 6712, and the King et al. object in NGC 6624) to the intense globular cluster X-ray sources, two of the objects are now thought to be unusual double-degenerate systems with ultrashort binary periods. Such systems are evidently far more rare among the intense binary X-ray sources in the field. Further identifications and follow-up of the counterparts to the intense X-ray sources in other globular clusters (e.g., Deutsch et al. 1996a, 1996b) may reveal whether such double-degenerates are truly overabundant, or merely that this initial hint is an artifact of the extremely small number of counterparts closely studied thus far.

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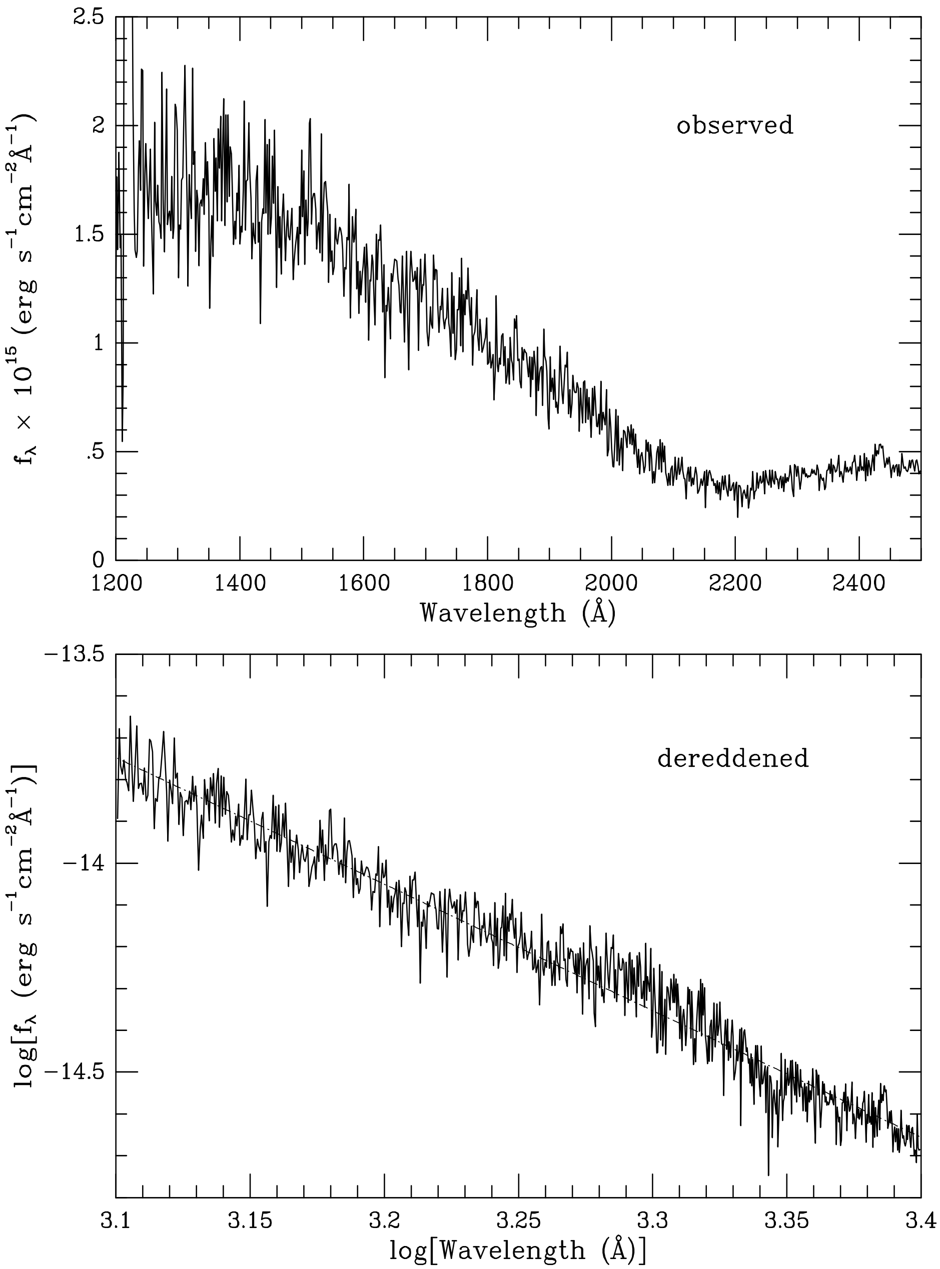


Fig. 1.— The time-averaged UV FOS spectrum of the King et al. counterpart to the X-ray source X1820-30 in the globular cluster NGC 6624. *Upper panel*: the observed spectrum is clearly that of a highly ultraviolet object, but few (if any) strong spectral features intrinsic to the object are seen. *Lower panel*: the dereddened spectrum, assuming $E(B-V) = 0.25$ as appropriate for NGC 6624; this spectrum is fit well by a power-law $f_\lambda \propto \lambda^{-3.0}$ (dashed-line), indicating a strongly rising spectrum slightly less dramatic than Rayleigh-Jeans.

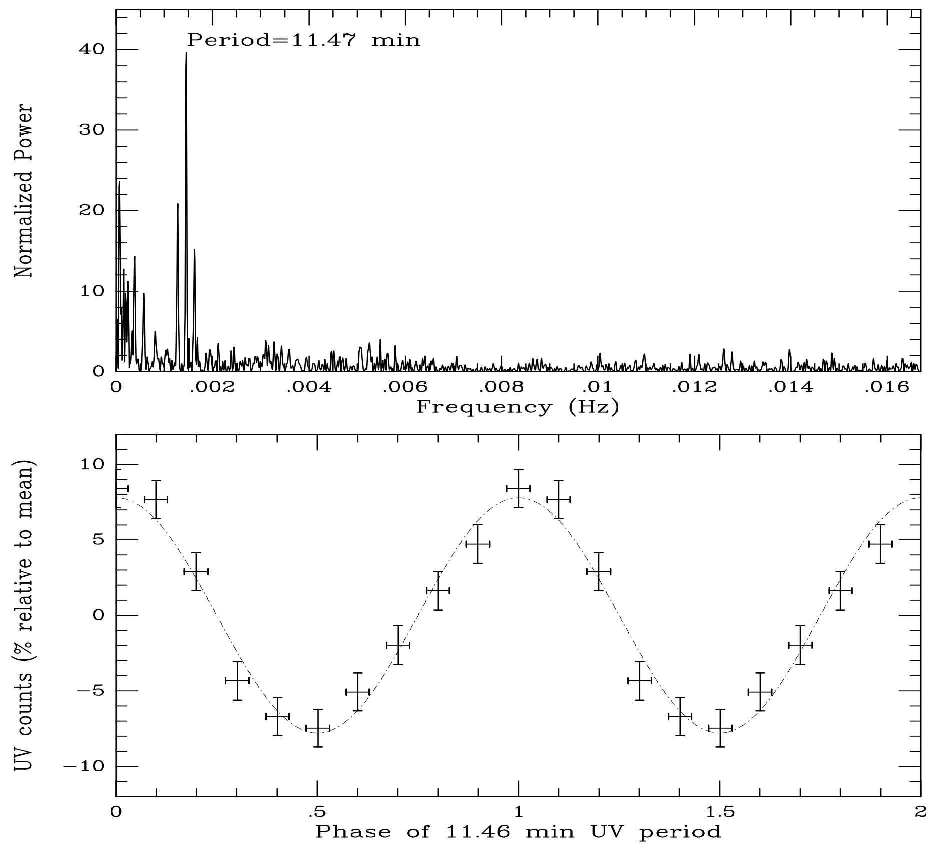


Fig. 2.— Fourier and least-squares analyses of the broadband FOS UV lightcurve. Eight hundred separate spectra were taken with time resolution ∼15 s. A simple measure of the UV broadband lightcurve was obtained by summing the counts within each of the 800 spectra across detector diodes corresponding to 1265-2510 Å. Fourier, PDM, and least-squares approaches all yield very strong detections of an 11 min periodicity in the UV lightcurve. *Upper panel*: the normalized Fourier power spectrum of the UV lightcurve. The strongest feature, of very high significance, is centered at 11.47 min; this UV period is very similar to that of the known X-ray period, confirming unequivocally that the X-ray source X1830-20 and the King et al. UV-bright object are associated. (The strong sidebands are beats with the 96 min *HST* orbital period). *Lower panel*: the UV lightcurve folded with a best-fit period and phase epoch (phase 0 chosen to be UV max) estimated from a non-linear least-squares fit. Ten independent phase bins across the 11 min UV period are displayed (but two cycles are shown with redundant data for clarity). *Horizontal error bars*: standard deviation in phase sampled by each of the 10 phase bins; *vertical error bars*: $\sqrt{N}$ expectations for the count uncertainties; *dashed curve*: best-fit sinusoid, with parameters obtained from fitting to all 800 data points of the UV lightcurve. This simple model fit yields a very large amplitude of 16% peak-to-peak in the UV (compared to $\sim 3\%$ for X-rays).